MULTIMEDIA UNIVERSITY®

STUDENT ID NO

MULTIMEDIA UNIVERSITY

FINAL EXAMINATION

TRIMESTER 2, 2022/2023

EME4016 – HEAT TRANSFER

(ME)

8 JULY 2023
9.00 a.m. - 11.00 a.m.
(2 Hours)

INSTRUCTIONS TO STUDENT

1. This Question Paper consists of six pages including the cover page and appendix.

2. Answer ALL four questions. Each question carries 25 marks and the distribution of the marks for each question is given in brackets **[ ]**.

3. Write all your answers in the Answer Booklet provided.

Question 1

A large metal plate of thickness $2L$ at a uniform temperature T_i = 240℃ is suddenly quenched by dropping it into a liquid bath of temperature, T_∞= 15℃. Heat transfer to the liquid is characterized by a convection coefficient, h= 40 W/m^2·K. It is given that $2L$ = 15 cm, plate density, ρ = 2770 kg/m^3, plate specific heat c_p = 875 J/kg·K, and plate thermal conductivity, k = 20 W/m·K. Assume that the temperature distribution is a function of spatial coordinate x, defined along the thickness of the plate, with the origin at the center and time, t.

(a) Determine the time required for the surface of the plate to cool to 140℃. **[12 marks]**
Note: You may find the following one-term approximation equations useful:

1. $\theta^* = \theta_o^* \cos(\zeta_1 x^*)$,

where θ_o^* represents dimensionless temperature of the plate at $x^* = 0$ and

$\theta_o^* = C_1 \exp(-\zeta_1^2 Fo)$.

C_1 and ζ_1 are coefficients depending on Biot number.

Fourier number, Fo and the dimensionless variables are defined as

$$\theta^* = \frac{T - T_\infty}{T_i - T_\infty},\ x^* = \frac{x}{L},\ Fo = \frac{\alpha t}{L^2}$$

2. The coefficients for the one-term approximation are given as follows:

Bi^*	ζ_1 (rad)	C_1
0.07	0.2615	1.0114
0.08	0.2791	1.0130
0.09	0.2956	1.0145
0.10	0.3111	1.0161
0.15	0.3779	1.0237
0.20	0.4328	1.0311
0.25	0.4801	1.0382
0.30	0.5218	1.0450

(b) What is the corresponding temperature gradient in ℃/m at the plate surface, x=L when the plate surface is at 140℃ ? **[5 marks]**

(c) If the plate is made of a different material with a smaller specific heat c_p and there is no significant change in other properties, how would your answer in part (a) be affected? Comment on the answer. **[3 marks]**

(d) If the left side of the plate is insulated, *sketch* the temperature distribution, T_1 on the plate at a stipulated time, t *clearly*. Also *sketch* the temperature distribution, T_2 for the cooled plate in (a) at the *same* t on the *same diagram*. Label the diagram *clearly*. Highlight the main differences between T_1 and T_2. **[5 marks]**

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Question 2

Hot air, at a mass rate of $\dot{m} = 0.04$ kg/s, flows in a 0.18-m diameter and 4-m long thin-walled copper pipe ducting. The hot air enters at 94 °C and exits at 66 °C. Assume all the heat from the air is transferred to the copper pipe, and fully developed conditions.

(a) Determine the heat transfer rate to the copper pipe, in W. **[6 marks]**

(b) Show that the flow is turbulent. **[4 marks]**

(c) What is the heat transfer coefficient for the hot air flow inside the pipe ? **[6 marks]**

(d) The exterior of the copper pipe is subject to an air flow characterized by a heat transfer coefficient, $h_o = 40$ W/m^2· K and $T_\infty = 5$°C. Estimate the local heat flux at the outlet of the pipe. **[6 marks]**

(e) How does the heat flux vary along the axial direction of the pipe? Substantiate your answer with calculations. **[3 marks]**

Note:

1. You may find the Appendix useful.

2. The Nusselt number correlation for the fully developed turbulent flow in smooth tubes is: $Nu_D = 0.023 Re_D^{0.8} Pr^n$, $n = 0.4$ for *heating* and 0.3 for *cooling*.

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Question 3

(a) A square chip, 15 mm by 15 mm, is cooled by air which approaches the chip at $T_\infty = 20$ °C with a heat transfer coefficient, $h = 8$ W/m^2·K. To increase the heat dissipation from the chip, a copper pin fin is metallurgically joined to the outer surface of the chip. The maximum allowable chip temperature is 85°C. The fin diameter, and length are $D = 5$ mm, and $L = 15$ mm. The thermal conductivity of the fin is, $k = 400$ W/m·K.
Assume the heat transfer is from the outer surface of the chip only, and take the fin efficiency as $\eta = \frac{\tanh(mL_c)}{mL_c}$ where L_c is the corrected fin length, by assuming equivalence to a hypothetical fin with an adiabatic tip, and $m = \sqrt{\frac{hP}{kAc}}$ with the symbols carrying the usual meaning.

(i) Show that the fin corrected length is, $Lc = L + \frac{D}{4}$. **[3 marks]**

(ii) What is the maximum heat transfer rate that can be dissipated from the outer surface of the chip when the fin is in place? **[10 marks]**

(b) A counterflow, concentric heat exchanger is designed to cool hot oil flowing at 4 kg/s from 120 °C to 60°C with chilled water supplied at a temperature of 15 °C and a flow rate of 2 kg/s. Take the specific heats for the water and oil as 4.186 kJ/kg ·°C and 2.2 kJ/kg ·°C respectively. Assuming an overall heat transfer coefficient of 1200 W/m^2·K, determine:

(i) the heat transfer rate, **[3 marks]**

(ii) the exit temperature of chilled water, and **[3 marks]**

(iii) the required heat transfer area. **[6 marks]**

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Question 4

Consider the radiative heat exchange inside a furnace in the shape of a vertical cylinder with an inside height of 0.50 m and an inside diameter of 0.25 m. The cylinder is open at the top end to the surrounding at 300 K. Surface *1*, the *bottom* end surface of the furnace, is at 800 K, and surface *2*, the *lateral* surface of the furnace is at 480 K. The emissivity of surface 1 is 0.8, while surface 2 may be approximated as a blackbody. It is known that F_{12} is 0.944. Treat the *top* opening as a hypothetical surface denoted as surface *3'*, and name the *surrounding* as surface *3*.

(a) Draw a suitable thermal radiation network for this furnace. **[5 marks]**

(b) Find $F_{13'}$, F_{21}, and F_{22}. **[6 marks]**

(c) Calculate numerically all the blackbody emissive power, relevant surface resistance and space(geometrical) resistance involved, including their correct units. **[7 marks]**

(d) Surface 1 and surface 2 are maintained at the temperatures through electrical heating, write down the equations and describe the steps required to solve for the electrical heating power required to maintain the condition of surface 1 and surface 2. DO NOT solve the equations. **[7 marks]**

Note: Take the Stefan-Boltzmann constant to be 5.67×10^{-8} W/m^2·K^4.

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Appendix: Properties of air at 1 atm pressure

Properties of air at 1 atm pressure

Temp., T, °C	Density, ρ, kg/m^3	Specific Heat, C_p, J/kg · °C	Thermal Conductivity, k, W/m · °C	Thermal Diffusivity, α, m^2/s	Dynamic Viscosity, μ, kg/m · s	Kinematic Viscosity, ν, m^2/s	Prandtl Number, Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-6}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Note: For ideal gases, the properties C_p, k, μ, and Pr are independent of pressure. The properties ρ, ν, and α at a pressure P (in atm) other than 1 atm are determined by multiplying the values of ρ at the given temperature by P and by dividing ν and α by P.

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Keenan, Chao, Keyes, Gas Tables, Wiley, 198; and Thermophysical Properties of Matter, Vol. 3: Thermal Conductivity, Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: Viscosity, Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenum, NY, 1970, ISBN 0-306067020-8.

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